

An early particle cosmologist



In mid-1930s, influenced by Eddington & Lemaitre, Schrödinger turned to cosmological issues

1938-1939: Graz → Vatican → Gent, Belgium → Dublin

The proper vibrations of the expanding universe

Erwin Schrödinger, *Physica* **6**, 899 (1939)

Introduction:

"... proper vibrations [positive and negative frequencies] cannot be rigorously separated in the expanding universe. ... this is a phenomenon of outstanding importance. With particles it would mean production or annihilation of matter, merely by expansion,... Alarmed by these prospects, I have examined the matter in more detail."

Conclusion:

"... There will be a mutual adulteration of positive and negative frequency terms in the course of time, giving rise to ... the 'alarming phenomenon'..."

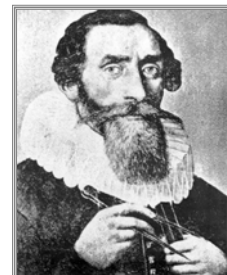
The proper vibrations of the expanding universe

Erwin Schrödinger, *Physica* **6**, 899 (1939)

Creation of a <u>single</u> pair of particles	$H \approx 60 \text{ km s}^{-1} \text{Mpc}^{-1}$
per Hubble volume	$V_H \equiv (c/H)^3 \approx 10^{12} \text{Mpc}^3$
per Hubble time	$t_H \equiv H^{-1} \approx 10^{10} \text{ years}$
with "Hubble energy"	$E_H \equiv \hbar H \approx 10^{-33} \text{ eV}$

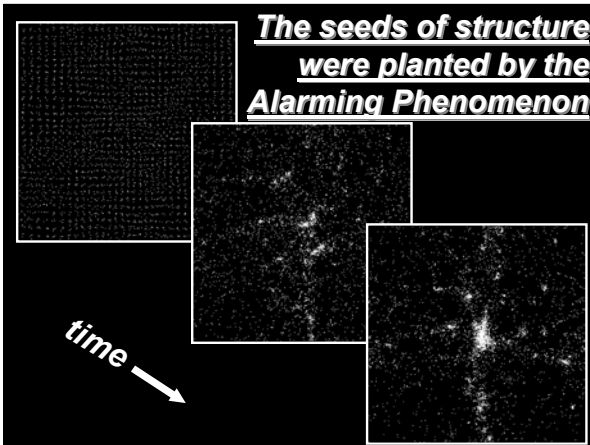
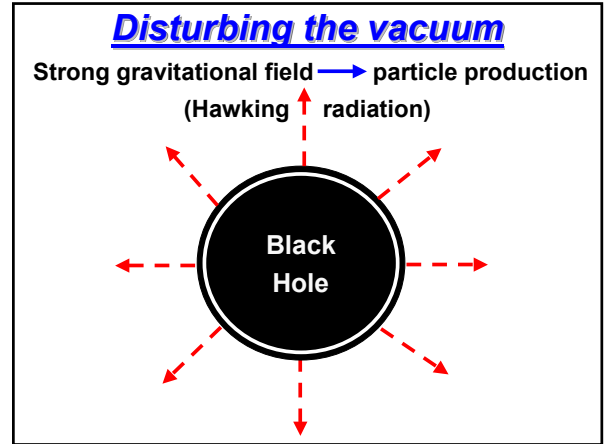
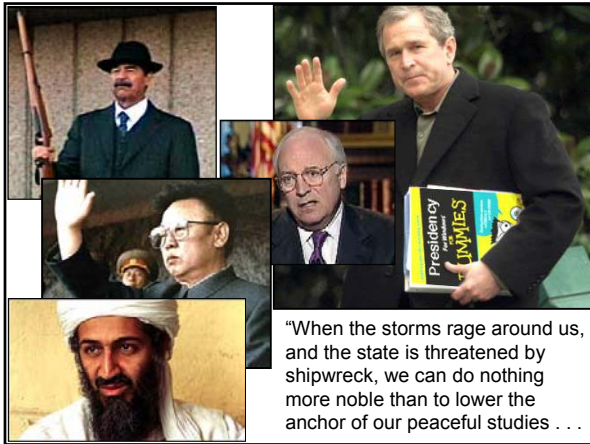
Alarming?

An even earlier Graz cosmologist



"When the storms rage around us, and the state is threatened by shipwreck, we can do nothing more noble than to lower the anchor of our peaceful studies in the ground of eternity." - J. Kepler

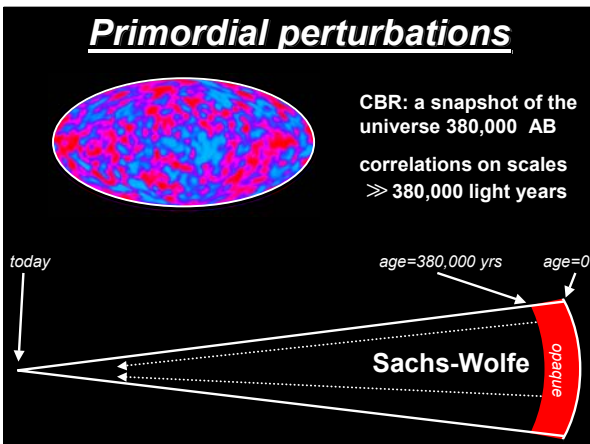
1600-1630: Graz → Prague → Linz → Sagan → Ratisbon



Simulation

Simulation (sɪmʊləˈʃən). ME. [a. OF., ad. L. *simulationem*.] *v.* The action or practice of simulating, with intent to deceive; false pretence, deceitful profession ME.

Oxford English Dictionary

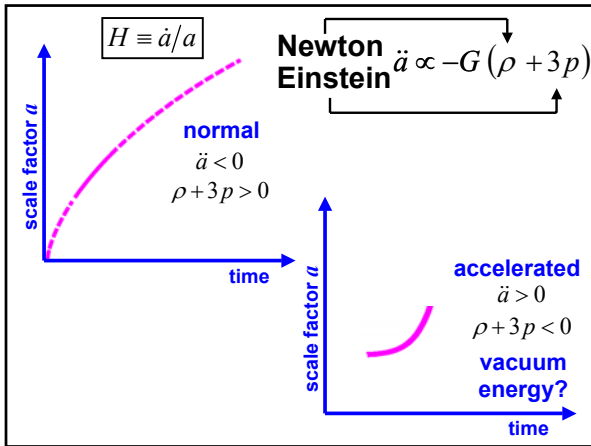


More than 380,000 light years in less than 380,000 years?

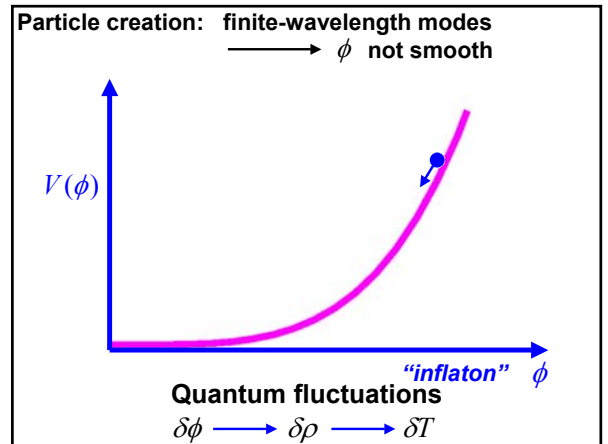
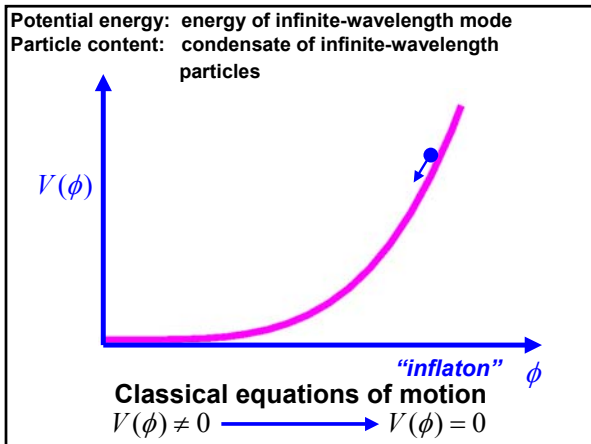
SPEED LIMIT

$v \leq c$

- $v \leq c$ for velocity through space
- no limit on expansion velocity of space
- "acausal" requires "accelerated" expansion



<u>Cosmic Symphony (Harmonice Mundi)</u>			
expansion tempo	movement	epoch	relic
pizzicato	string dominated $H \approx ???$	10^{-43} sec.?	???
presto	vacuum dominated (inflation) $H \approx \text{const}$	10^{-35} sec.?	CBR fluctuations, gravitational waves, seeds of structure
allegro	radiation dominated $H \approx a^{-2}$	earlier than 10,000 yrs.	abundance of the light elements
andante	matter dominated $H \approx a^{-3/2}$	later than 10,000 yrs.	distant quasars and galaxies
largo	vacuum dominated (inflation) $H \approx \text{const}$	day before yesterday	acceleration of the universe



The alarming phenomenon

Einstein gravity \longrightarrow \longrightarrow Inflaton field

$$S = \int d^4x \sqrt{-g} \left[-\frac{M_{Pl}^2}{16\pi} R + \frac{1}{2} (\partial\phi)^2 - V(\phi) \right]$$

$$g_{\mu\nu}(\vec{x}, t) = g_{\mu\nu}^{FRW}(t) + \delta g_{\mu\nu}(\vec{x}, t)$$

$$\phi(\vec{x}, t) = \phi_0(t) + \delta\phi(\vec{x}, t)$$

Tensor perturbations (gravitational waves) $v(\delta g_{ij})$
in terms of $v \propto$ gravitons

$$S = \int d^4x \left(\partial_\mu v \partial^\mu v - \frac{1}{2} m_v^2 v^2 \right) \quad \text{Minkowski space (conformal time)}$$

m_v^2 changes because of expansion

The conformal time zone: τ

Robertson - Walker metric: $ds^2 = dt^2 - a^2(t) d\vec{x}^2$

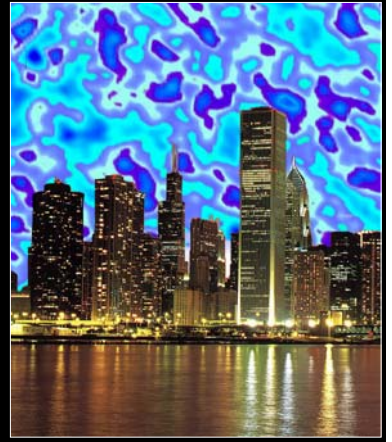
$$dt^2 = a^2 d\tau^2 \quad ds^2 = a^2(\tau) (d\tau^2 - d\vec{x}^2)$$

all structures in the universe arise from



“Schrödinger’s alarming phenomenon”

A pattern
of
vacuum
quantum
fluctuations
(the alarming
phenomenon)



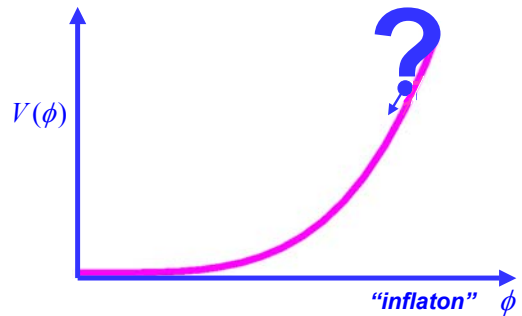
**Origin of structure:
a complex natural phenomenon**

**Perturbations from inflation:
a simple, elegant, compelling
explanation**

**“For every complex natural phenomenon
there is a simple, elegant, compelling,
wrong explanation.”**

- Tommy Gold

Who is the inflaton?

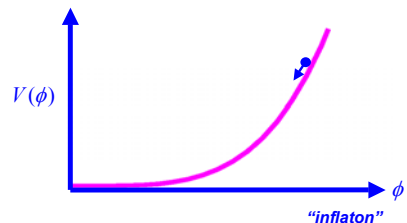


**Top down
(superstring
inspired)**

inspired: as if prompted by
or emanating from a
supernatural source.
(Oxford English Dictionary)

**Bottom up
(phenomenology
perspired)**

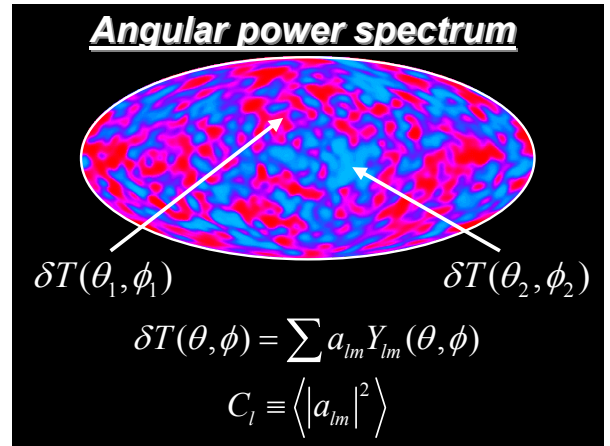
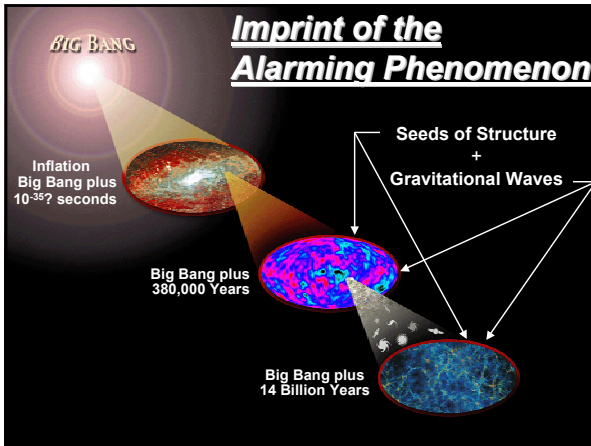
Inflation phenomenology



Inflaton
Potential



**seeds of structure
(creation of inflaton quanta)
gravitational waves
(creation of graviton quanta)**



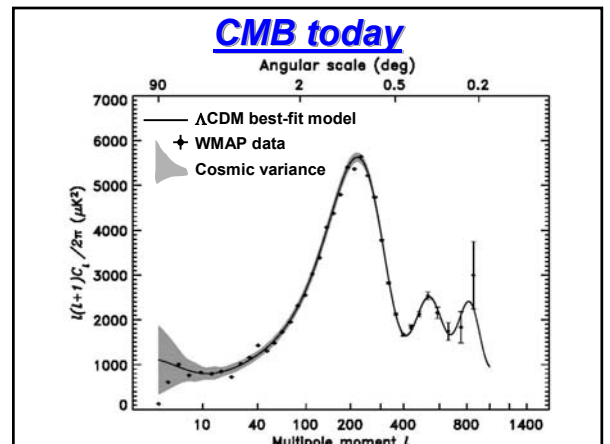
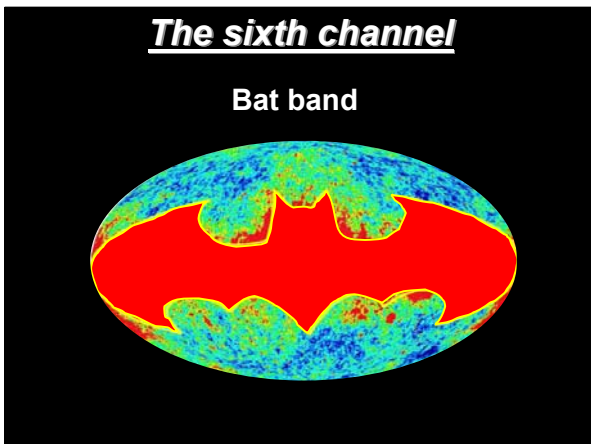
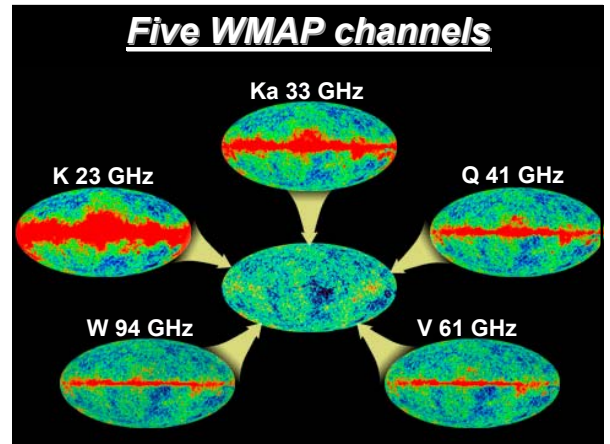
Wilkinson Microwave Anisotropy Probe

David T. Wilkinson
1935-2002

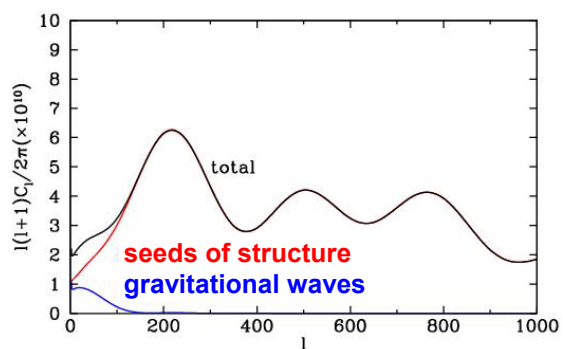
WMAP model
MIDEX

WMAP science team

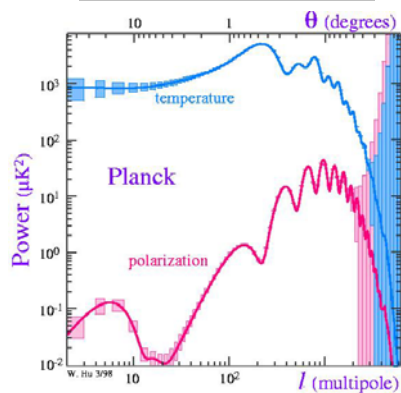
http://map.gsfc.nasa.gov/m_mm/pub_papers/firstyear.html



Angular power spectrum



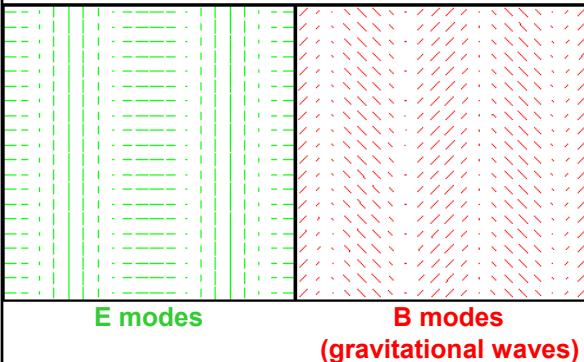
CMB polarization



CMB polarization

Stebbins, Kosowsky, Kamionkowski

Seljak & Zaldarriaga



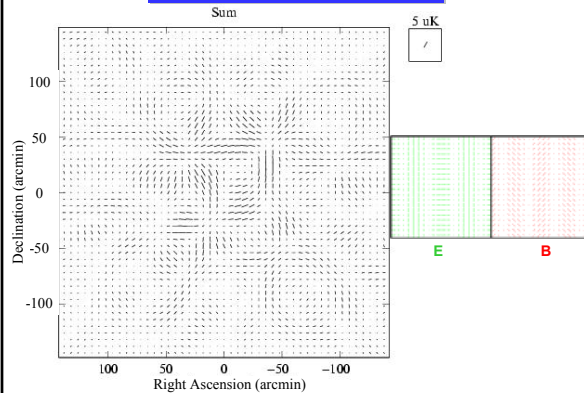
CMB polarization

DASI : astro-ph/0209478...Also WMAP!

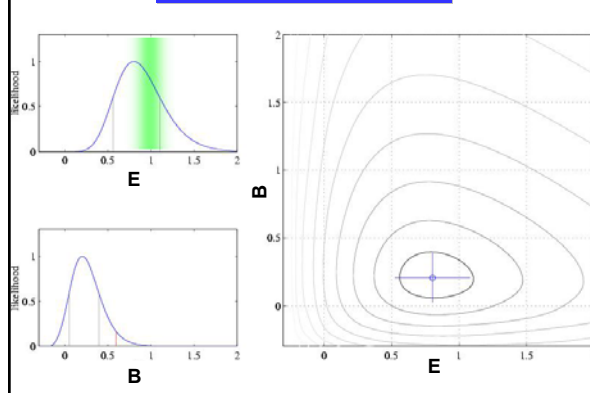


Kovac, Leitch, Pryke, Carlstrom, Halverson, Holzapfel

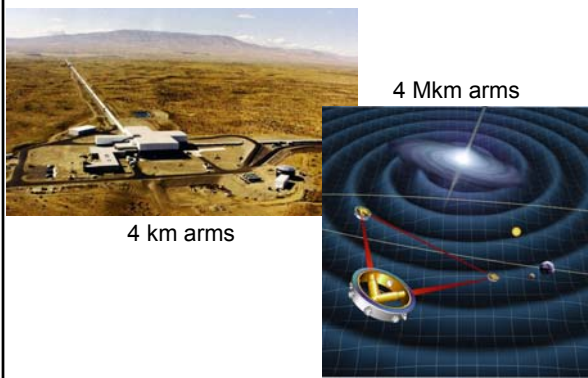
CMB polarization



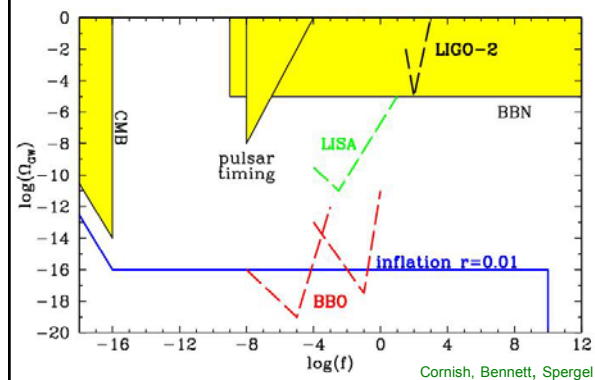
CMB polarization



LIGO → LISA → BBO



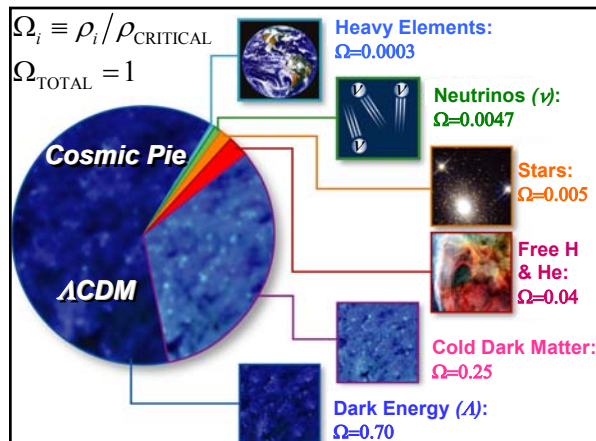
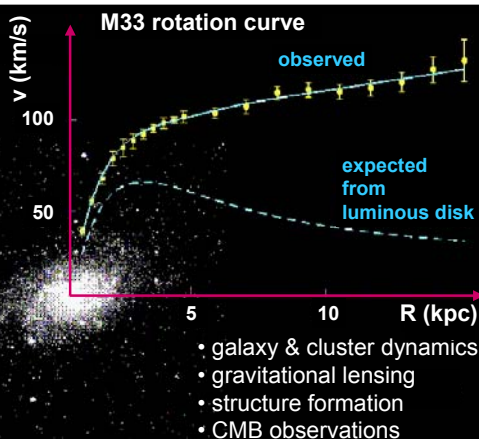
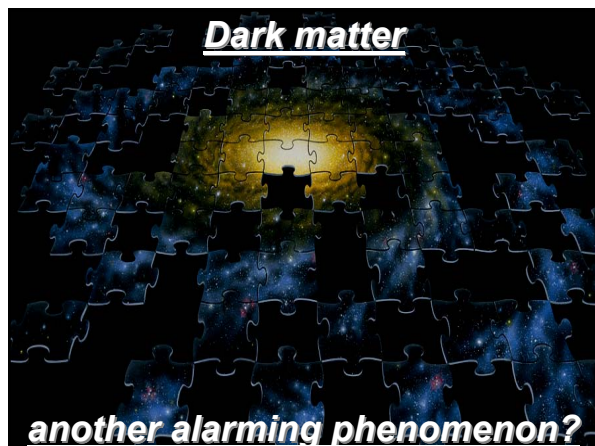
LIGO → LISA → BBO



Comparison to observation:

- ✓ 1. a (nearly exact) power-law
- ✓ 2. spectrum of gaussian
- ✓ 3. super-Hubble-radius
- ✓ 4. scalar perturbations (seeds of structure) &
- 5. tensor perturbations (gravitational waves)
- 6. related by a consistency relation
- ✓ 7. in their growing mode
- ✓ 8. in a spatially flat universe.

Dark matter



Cosmo-illogical constant

Mass density of space:

$$\rho \simeq 10^{-30} \text{ g cm}^{-3}$$

The unbearable lightness of nothing!

Dark energy depression?

1. Alcohol*
2. Drugs*
3. Anthropic principle*
4. Creative theories
5. Hard experimental work
6. Observational direction

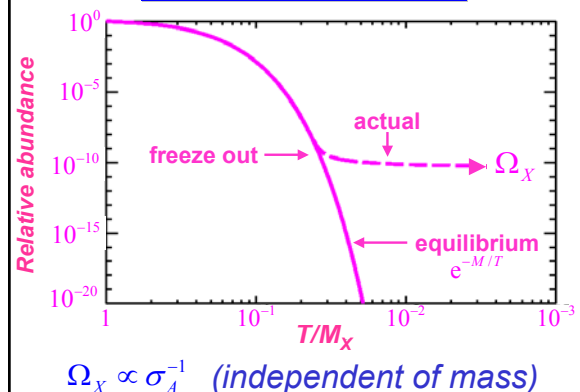
* Therapy, medication, and twelve-step programs available.

Dark matter candidates

- Modified Newtonian dynamics?
- Planets?
- Mass disadvantaged stars?
 - brown red white
- Black holes?
- Dark baryons?
- Nonbaryonic particle dark matter?



Cold thermal relics



**“For every complex natural phenomenon
There is a simple,**

Alarming phenomenon of particle creation

(Arnowitz, Birrell, Bunch, Davies, Deser, Ford, Fulling, Grib, Hu, Kofman, Mostepanenko, Page, Parker, Starobinski, Unruh, Vilenkin, Wald, Zel'dovich,...)

first application: { density perturbations from inflation
gravitational waves from inflation

(Guth & Pi; Starobinski; Bardeen, Steinhardt, & Turner; Hawking; Rubakov; Fabbri & Pollack; Allen)

new application: dark matter

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

- require (super)heavy particle “X”
- stable (or at least long lived)
- initial inflationary era followed by radiation/matter

Superheavy particles

- Inflaton mass (in principle measurable from gravitational wave background, guess 10^{12} GeV) may signal a new mass scale in nature.
- Other particles may exist with mass comparable to the inflaton mass—natural to have $\Omega = 1$.
- Superheavy **DARK MATTER!**
- Abundance independent of interactions

<u>undetectable?</u>	<u>detectable?</u>
	<ul style="list-style-type: none"> • direct/bulk • UHE cosmic rays • annihilation <ul style="list-style-type: none"> – galactic center, sun • other signals?



Isocurvature modes:

CMB, Large-scale structure

Decay:

Ultra High Energy Cosmic Rays

Annihilate:

Galactic Center, Sun

Direct Detection:

Bulk, Underground Searches

Dark Matter

WIMP

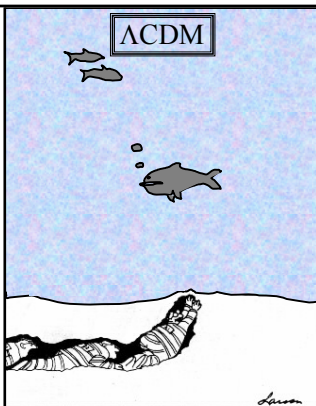
or

WIMPZILLA



The alarming phenomenon

- The “alarming phenomenon” may produce seeds of structure
 - astrophysical signatures of the quantum vacuum
- The “alarming phenomenon” may produce dark matter.
 - dark matter may be **WIMPZILLAS!**
 - WIMPZILLAS may be undetectable!
 - but then again, they may be detectable!



We're almost free, I just felt the first drops of rain

Inner space / Outer space



<http://home.fnal.gov/~rocky/ucla.pdf>